

On the theory of high and low pressure areas: The significance of divergence in pressure areas

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Original citation:

SCHERHAG, R., 1934: Zur Theorie der Hoch- und Tiefdruckgebiete. Die Bedeutung der Divergenz in Druckfeldern. – Meteorol. Z. **51**, 129–138.

Suggested citation:

SCHERHAG, R., 1934: Zur Theorie der Hoch- und Tiefdruckgebiete. Die Bedeutung der Divergenz in Druckfeldern (On the theory of high and low pressure areas: The significance of divergence in pressure areas). – Meteorol. Z. **51**, 129–138. (translated and edited by VOLKEN, E., A.M. GIESCHE, S. BRÖNNIMANN. –Meteorol. Z. **25** (2016), DOI:10.1127/metz/2016/0785).

Abstract

This is the edited and translated version of the article by RICHARD SCHERHAG “Zur Theorie der Hoch- und Tiefdruckgebiete. Die Bedeutung der Divergenz in Druckfeldern” (On the theory of high and low pressure areas: The significance of divergence in pressure areas), which was published in *Meteorologische Zeitschrift* **51**, 129–138.

Keywords: Classic paper, Scherhag, pressure areas, divergence

Superscript numbers indicate original footnotes (translated at the bottom of the page), E... numbers indicate editorial endnotes (at the end of the article), square brackets [] indicate editorial comments in the text.

The question of what causes pressure variations remains a basic problem regarding the explanation of the development and mass balance of pressure areas. According to PALMÉN's^{1,E1} definitions, one can juxtapose the thermally caused pressure changes with the group of dynamic pressure variations that are not directly caused by temperature. The consideration that any pressure change in an area primarily caused by a change in temperature must be accompanied by an equally large pressure change in a neighbouring zone due to the constancy of the mass, shows that the thermal and dynamic effects must be at least of the same order of magnitude. The well-known cyclic process between differentially heated areas² also strongly suggests that pressure is equalised at medium height, meaning that “static compensation” accounts for only about half the value. Taking into consideration the centrifugal force caused by the Earth's rotation and bearing in mind that the Earth's surface repre-

sents the main level of compensation,³ it becomes obvious that only a small proportion of pressure changes can be explained thermally. Further support comes from the high positive correlation coefficients that DINES^{4,E3} and SCHEDLER⁵ found between the pressure at 9 km altitude and mean tropospheric temperature.

The considerations about the minimal effect of “thermal” air pressure variations also apply, without reservation, to the stratosphere. In various studies, PALMÉN⁶ has interpreted the inverse relationship between stratospheric temperature and air pressure as a necessary consequence of tropospheric effects. The result found by SCHEDLER (l.c.) supports the assumption that dynamic processes also predominate in the stratosphere. SCHEDLER calculated the pressure effects of single at-

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¹E. PALMÉN, Aerologische Untersuchungen der atmosphärischen Störungen. Mitt. D. Meteorolog. Instituts d. Universität Helsingfors Nr. 25, 1933.^{E2}

²cf., for instance, HANN-SÜRING, Lehrbuch d. Meteorologie, 4th ed.^{E2}, p. 430, Figures 36 and 37.

³cf., in particular F.M. EXNER, Dynamische Meteorologie, 2nd ed.^{E2}, p. 132 and 286.

⁴W.H. DINES, The Vertical Distribution of Temperature in the Atmosphere over England. Brit. Met. Off., Geophys. Memoirs no. 2^{E2}; furthermore: The Characteristics of the free Atmosphere. Ibid. no. 13, 1919^{E2}.

⁵A. SCHEDLER, Über den Einfluss der Lufttemperatur in verschiedenen Höhen auf die Luftdruckschwankungen am Boden. Beitr. z. Phys. D. freien Atmosph. 7, 88, 1917.^{E2}

⁶E. PALMÉN, Die Beziehungen zwischen troposphärischen und stratosphärischen Temperatur- und Luftdruckschwankungen. Beitr. z. Phys. d. freien Atmosph. 17, 102, 1931.^{E2} – Versuch zur Analyse der dynamischen Druckschwankungen in der Atmosphäre. Ibid. 19, 55, 1932.^{E2}

mospheric layers and found remainder terms suggesting that more than half of the pressure variations take place at heights above 14 km. It is particularly remarkable that the stratospheric pressure effects rapidly decline above 11 km, and it is not evident until what height the compensation takes place. EXNER^{7,E4} leaves open the question of whether the remainder term results from observation bias, or if the atmosphere shows depressions and bulges at higher altitudes, meaning that the pressure effects would be largely of a purely dynamic nature.

We are inevitably confronted with the question of how pressure differences resulting from dynamic causes can occur at all. These pressure differences represent the main part of weather phenomena. The air mass balance of atmospheric pressure areas already appears as a predominantly dynamic effect, on the basis of which we have to try to answer the question of how the air masses flowing in or out over the ground are replaced from higher altitudes. SHAW^{8,E5} calculated the amounts of descending air in a high pressure area between 86 m a.s.l. and 450 m above England per day. The calculated value for the 450 m height would correspond to a daily pressure decrease of 50 mb, unless the same amount of air replaced it. These vertical air movements must be significantly greater in a low pressure area, which was shown by a rough estimate in the study of a Baltic Sea storm.⁹

Regarding these vertical air movements within atmospheric pressure areas, one must consider that the primary cause for the generation and continuity of the pressure contrast must be located at higher altitudes, since pressure equalization inevitably occurs on the ground. Thus, the phenomenon that cirrus clouds move anticyclonically above a high pressure area¹⁰, whereas the air moves cyclonically on the level of the upper clouds above a low pressure area¹¹, must be causally related to the formation of high and low pressure areas. It is of particular interest to understand how these flow patterns are possible at all.

The relation between upper air flow and pressure change. A study of the Baltic Sea storm of July 8th/9th, 1931¹², showed a remarkable agreement between the location of the area of pressure drop and diverging flow discernible at a higher level. Numerous similar cases show the same striking relation. In the following section, one of these examples, showing how synoptics draws attention to the relation between air pressure tendency and flow field, shall be discussed.

On this day [Dec 11th, 1931], the [west-east] pressure contrast over Central Europe was exceptionally high, with small differences on the ground due to extraordinary temperature contrasts at higher altitudes. Wind

speeds reached more than 40 m/sec at 5000 m a.s.l., and increased to nearly 70 m/sec near the stratospheric boundary.

What is particularly remarkable about the map is the form of the isobars, which are closest to each other along the 50th degree of latitude, so that the pressure field shows a pronounced convergence over the Baltic and the North Sea, and a divergence over southern Europe. Fig. 1b represents the barometric tendency according to the weather forecast of the German naval observatory, and one recognizes the striking agreement between the convergence zone and the area of pressure increase. One sees that the pressure drops in the area of the diverging wind field.

The areas of changing pressure naturally move with the predominant northerly flow – on the eastern slope of the dominant English high pressure area to the south. In the examples where the low pressure area moves from west to east, divergence and convergence follow each other in the corresponding order; many such examples can be found in the daily upper level charts of the meteorological service.

It is evident that such a relation between pressure change and flow field must exist. In Fig. 2, the isobars p_1, p_2, \dots indicate a divergent pressure field in the upper layers that is supposed to be stationary, so that the upper level flow moves across the gradient field. The gradient that affects the air particles weakens in the flow from left to right. This decrease of the gradient force cannot be related to a decrease in the flow velocity, since the airflow is subject to inertia, and the friction in the upper layers is not able to cause a relevant deceleration (shown by the afore-mentioned calculation for the Baltic Sea storm). At first, a necessary consequence of the predominance of the Coriolis force over the gradient force is a clockwise rotation of the wind. Neglecting the effects on the borders, this forcing will not cause any pressure changes, since the deflection within the observed field is equal everywhere if the angles between the single isobars are equal.

Evidently, the entire flow will slow down, since the clockwise rotation of the flow results in a component going against the gradient. However, this component results from the fact that the velocity is too high, and it can only weaken the positive divergence caused by the high velocity. The flow velocity cannot decrease to the same extent that the cross section of the flow line field increases. Therefore, there must be a mass loss per area unit, and, consequently, a pressure drop. Accordingly, any convergent upper air flow must go together with a mass input. (The pressure changes are, of course, not the direct consequence of the mass changes, but rather occur due to the immediate vertical pressure equalisation via the detour over the stratosphere, as was convincingly described by PALMÉN l.c.)

RYD's theory about cyclones. This notion about the development of pressure changes closely ties in with

⁷Dynamische Meteorologie^{E2}, 2nd ed., p. 304.

⁸N. SHAW, Manual of Meteorology, Vol. II, p. 341.^{E2}

⁹Appearing shortly in: Annalen d. Hydrographie.^{E6}

¹⁰cf. HANN-SÜRING, Lehrbuch d. Meteorologie. 4th ed.^{E2}, p. 576

¹¹Ibid. p. 542.

¹²Appearing shortly in: Annalen d. Hydrographie.^{E6}

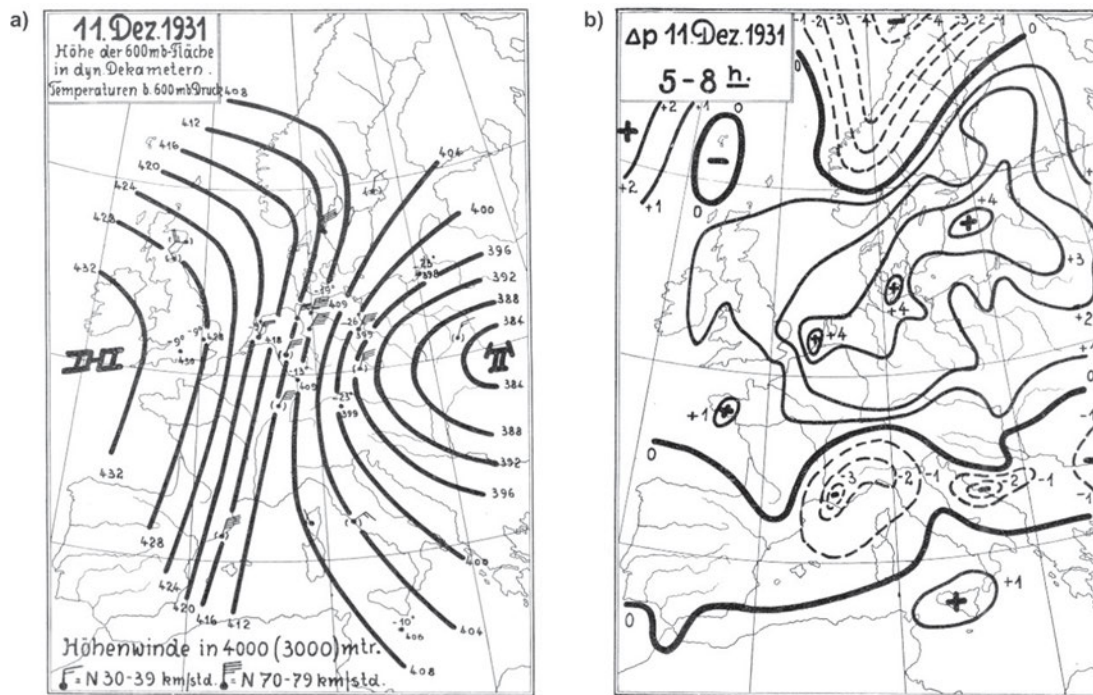


Figure 1: [(left) Geopotential height (solid lines) and temperature (numbers) at 600 hPa as well as winds at 4000 m (3000 m) and (right) pressure tendency on 11 December 1931]^{E7} The solid lines in a) represent the absolute topography of the 600 mb surface on December 11th, 1931. It was calculated by graphical addition of the absolute topography of the 1000 mb surface and the relative topography of the 600 mb surface above the 1000 mb surface, and was drawn for a distance of four dynamic decametres each. The distance of the isolines then corresponds to the distance of the ground isobars of 5 mb, which facilitates an overview. Besides the locations of aerological ascent, the directly calculated values of the level of the 600 mb surface are included, as well as the temperatures measured at a pressure level of 600 mb. Regarding the feathers of the wind arrows, one full stroke corresponds to a wind velocity of 20 to 29 km per hour.

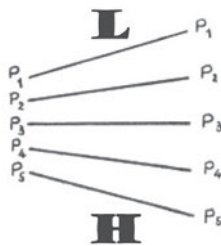


Figure 2: [Schematic figure showing isobars p in a diverging pressure field]^{E7}

RYD's theory.¹³ However, RYD does not consider the processes within divergent pressure fields, but rather at their borders. He does this by deriving pressure increase on the right side and pressure drop on the left side in the case of a deflection to the right due to positive divergence. This effect does, of course, occur, and weather charts often show it very clearly. However, if it were the primary effect, then all areas of pressure drop would have to be accompanied by an area of pressure increase on their right side, which is not the case. Rather, the predominant correlation is between the area of pressure

drop and the subsequent area of pressure increase, or between an area of pressure increase and a subsequent area of pressure drop. The air masses flowing out of the area of pressure drop will have to accumulate in the subsequent or previous area of pressure increase, as the velocity here increases too slowly by the same amount as it decreases too slowly in the area of divergence. This is why we observe the pressure increase in the entire area of convergence and not only at its border in all examples.

With regard to the remaining points, however, we do closely follow the notion of RYD, in particular with regard to the view that the transfer of energy in cyclones takes place by means of the upper air flow. RYD also points out that a strong upper air flow is generated in the zones with large temperature differences. As has already been mentioned, this can be explained by the fact that the pressure contrasts are very large above air masses of different temperatures, particularly in the upper layers.

The formation of cyclones in the “delta” of frontal zones. From what has been said, it is evident that cyclones can develop only at frontal zones, of the kind introduced in meteorology by BERGERON.^{14,E8} In Fig. 3a, the dotted lines represent the course of the isothermal characteristics before the cyclone formation in such an area. The solid lines represent the undisturbed isobars at

¹³V.H. RYD, Meteorological Problems, 1. Travelling Cyclones. Publikationer fra det Danske Meteorologiske Institut, Meddelelser no. 5, 1923^{E2}. 2. The Energy of the Winds, ibid. no. 7, 1927^{E2}; s. in particular p. 73–82 and Fig. 21 on p. 82.

¹⁴T. BERGERON, Über die dreidimensionale verknüpfende Wetteranalyse. Geofysiske Publikasjoner Vol. V, no. 6.^{E2}

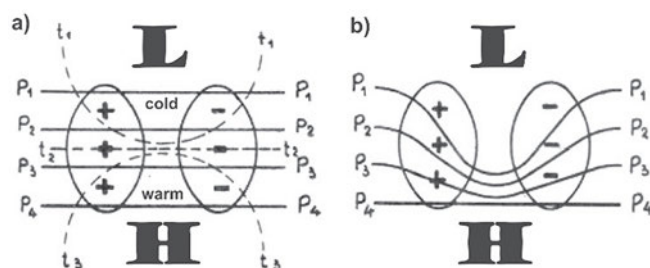


Figure 3: [Schematic figure showing cyclone development in the “delta” of frontal zones. Letters p and t denote isobars and isotherms, respectively]^{E7}

ground level. The isobars have to adapt to the isotherms with height, resulting from a pronounced divergence of the high altitude wind in the “delta” of any frontal zone, and a strong convergence of the upper pressure field in the “basin” of a frontal zone. Cyclone formation, which must start with a pressure drop, is therefore only possible on the divergent side of a frontal zone. SCHINZE^{15,E9} insistently points at the significance of the hyperbolic point and notices, “that in the eastern branch of a frontal zone, fast running wave interferences will develop, whereas in the western branch, the front remains quasi-stationary.” The explanation for this is evident in our scheme, and one cannot suggest the formation of a cyclone or a strong pressure drop from a strong temperature difference alone; in the case of converging isotherms, the pressure will actually rise.

Pressure changes on both sides of the frontal zone will be immediately noticeable in the ground pressure field where, in the case of a sufficient intensity of the pressure decrease and with the additional support of centrifugal acceleration and the Coriolis force, a closed vortex centre may form and compensate the temperature differences. When the occlusion is complete, the indentation of the isobars reaches its maximum. As shown in Fig. 3b, there is still a pronounced divergence on the front of such a cyclone, which is the reason why a cyclone persists for some time even after the occlusion, namely until its kinetic energy is used up by friction.

Isothermal divergence and pressure drop. We have seen that the pressure on the backside of a frontal zone must drop due to the divergence of the upper field of isobars: this divergence results from the divergent temperature distribution. With regard to weather prediction, it is very important to determine the zones of divergent high altitude winds. Yet, if there are not enough high altitude wind measurements available for the area of the frontal zone, then the isotherms can be used for weather prediction. However, this is only possible during the warm season in rural areas, when ground temperatures are representative for the free atmosphere. Cyclone formation does not depend on particularly large temperature con-

trasts. It is rather the divergence at the front’s border that is decisive. The isothermal characteristics are an excellent criterion, particularly with regard to the formation of Vb-depressions, as will be shown in a future publication by means of numerous examples. In a short contribution in this journal¹⁶, the data of some particularly remarkable cases are already given.

The drop theory of cyclones. The study of the Baltic Sea storm showed that the isothermal divergence, in this case, was caused by the drop-shaped advance of cold air, which was consistent with EXNER’s view.¹⁷ A high-altitude divergence can, of course, just as well be caused by a cold air wedge as by a warm sector. EXNER believed, however, that the cyclone can form on the lee side of the cold air pool because of negative pressure due to the obstacle created by the westerly current. However, counter to EXNER’s view, cold air wedges never reach a high altitude, and the pressure above them is generally quite low even at medium altitudes, which prevents them from acting as obstacles.

Centres of action and isothermal characteristics.

The low pressure system over Iceland also lies within an area of pronounced isothermal divergence. The temperature in the west of the British Islands decreases along the meridian, whereas further to the north, the lines of equal air temperature closely follow the eastern coast of Greenland. Similar conditions can be found along the eastern coasts of America and Asia precisely where the main origins of the northern hemispheric cyclones are located, whereas the Asiatic anticyclone is located where the isotherms converge most strongly in winter. The agreement is remarkable, and is particularly pronounced in winter between the zone of extreme isothermal divergence of water temperature east of Newfoundland¹⁸ and the greatest storm frequency¹⁹ in this area.

GUILBERT’s rule about divergent winds. The signal of an isobaric divergence at higher altitudes will always appear in the ground pressure field if the temperature conditions are balanced. GUILBERT’s rule^{E10} that the pressure will drop in the area of divergent winds, appears to be a special case of high-altitude divergence. However, SCHINZE²⁰ and WAGEMANN²¹ believe that the pressure drop in the area of divergent winds is to be considered as the necessary consequence of an approaching cyclone. The fact that an explanation for GUILBERT’s rules of the second kind is still missing – ERTEL²² has

¹⁶1933, Issue no. 12.^{E11}

¹⁷Dynamische Meteorologie, 2nd ed.^{E2}, p. 277 ff.

¹⁸Cf., for instance, G. SCHOTT, *Geographie des Atlantischen Ozeans*, 2nd ed.^{E2} Table IX.

¹⁹Ibid. p. 226, Figure 274.

²⁰A. a. O., p. 59.

²¹H. WAGEMANN, *Die Begründung und Brauchbarkeit der Guilbertschen Regeln*. Meteorol. Zeitschr. 49, 262, 1932.^{E2}

²²H. ERTEL, *Theoretische Begründung einiger Guilbertscher Regeln*. Tätigkeitsbericht des Preussischen Meteorologischen Instituts 1929, p. 114.^{E2}

¹⁵G. SCHINZE, *Die praktische Wetteranalyse*. Archiv d. Seewarte 52, no. 1, 49, 1932.^{E2}

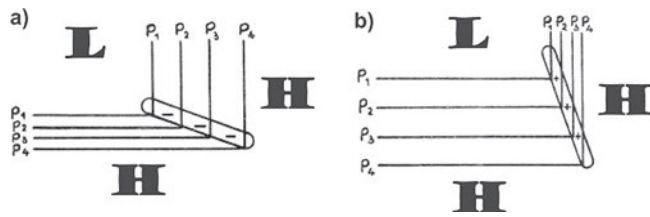


Figure 4: [Schematic figure showing the propagation velocity of wind divides. Letter p denotes isobars]^{E7} a) A strong current advances towards a weak one. b) A weak current is not able to advance against a strong one.

already provided proof for the rules of the first kind – cannot be used to question their prognostic significance, which DEFANT²³ particularly emphasizes. Furthermore, our conclusion has been confirmed, namely that GUILBERT's rules are the best indicator for the track of occluded fronts. The different propagation velocities of wind divides are based on the same principle.

The propagation velocity of wind divides. Fig. 4a shows the course of the isobars at a wind divide, of which we would say “that the westerly current will push eastwards due to its greater velocity”. However, no current can spread unless there is a pressure distribution allowing expansion at its front. In particular, if the focus is put on the analysis of air masses, it is easy to mistakenly treat them as “rigid bodies” and neglect the pressure changes that are required to enable the advance of air masses.

As shown by schematic Fig. 4a, the distance between isobars suddenly increases at such a front. Thus, a pronounced divergence occurs in front of a wind divide, which causes pressure to drop and therefore favours a rapid propagation of the more quickly moving air mass.

The opposite happens if velocity is higher before rather than after the change of direction (Fig. 4b). In this case, there is convergence along the trough, and the further movement of the wind divide is hindered and only possible if strong temperature contrasts at high altitudes cause an entirely different, that is to say divergent, pressure field.

Acceleration and pressure change along fronts. In Figs. 5a and 5b, the dotted lines ($p_1 \dots$) indicate the initially undisturbed ground isobars. In Fig. 5a, there is a warm front in the centre of the field, and in Fig. 5b there is a cold front in the centre of the field indicated by the vertical dotted lines ($t_1 \dots$). In both figures, the solid lines schematically show the course of the isobars at higher altitudes ($p'_1 \dots$). One can immediately see that the upper air flow must be strongest within the frontal zone, rapidly decrease at the forefront, and be weaker at the backside. Due to the resulting divergence, the pressure must drop ahead of every front and increase behind it. There is no fundamental difference between

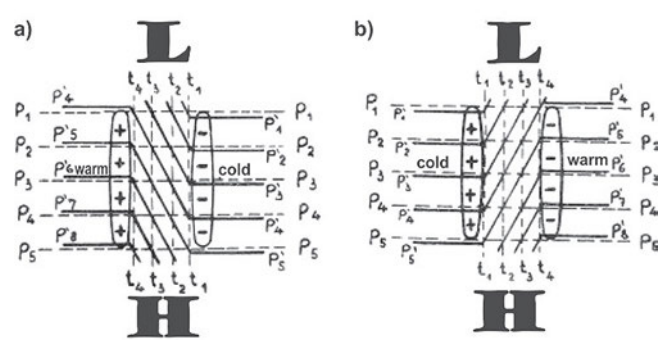


Figure 5: [Schematic figure showing the acceleration of pressure changes along fronts. Letters p and t denote isobars and isotherms at the surface, p' denotes isobars at higher altitudes]^{E7} a) Development of pressure changes along a warm front. b) Development of pressure changes along a cold front.



Figure 6: The large divergence at a triple point.

a warm and a cold front, only that the upper air flow is accelerated to the right in one case, and to the left in the other. The steeper the angle is at which isobars and isotherms intersect, the larger are the pressure changes at the front.

It has long been known from meteorological services that the pressure ahead of cold fronts drops just as much as ahead of warm fronts – maybe even more due to larger temperature differences. This fact has now found a simple interpretation.

Furthermore, we can learn from the previously-discussed figures that the location of the areas with changing pressure will lead to the formation of a low pressure trough at the front.

The divergence at the triple point. It is also easy to understand the known phenomenon that the strongest pressure drop must occur at the triple point, and that the greatest possibility of the development of a partial cyclone is located here. As shown in Fig. 6, the flow divergence, which always occurs at the tip of a warm sector, adds to the frontal divergence at the point of forking. Since, as has been recently pointed out by ROEDIGER²⁴, the upper air flow is almost always parallel to a front, high altitude winds must occur as shown in Fig. 6.²⁵ The divergence reaches its highest level ahead of the triple point so that the pressure drop is greatest just ahead of this point.

²³A. DEFANT, Wetter und Wettervorhersage, 2nd ed. ^{E2}, p. 255.

²⁴G. ROEDIGER, Bestimmung der Höhenwinde in 5 bis 10km nach der Verteilung der Luftkörper. Annalen d. Hydrogeographie 61, 338, 1933. ^{E2}

²⁵The occluded part of the front can be considered as a cold front, because lifted warm air is quickly turned into cold air due to dynamic cooling.

Consequences for the air mass balance of pressure centres. From the given analyses, one cannot conclude that the upper air flow is always strongest above a low pressure area and weakest above a high pressure area. This may be true for the average case, which results from the fact that low pressure areas show the largest temperature differences within their surroundings. From this conclusion, ANGOT²⁶ derived the large pressure contrasts at higher altitudes above depressions. Accordingly, the upper clouds on the front side of a low pressure area always diverge, which I have already mentioned in this journal.²⁷

Pressure changes always depend on the relationship between inflowing and outflowing air masses, that is, on the total divergence in an air column. A high pressure area can only be reinforced if more air is flowing into the upper layers than there is flowing out of the lower layers. In accordance with the preceding argument, a convergent upper air flow always has to be related to a mass input. Recently, MICHEL²⁸ proved in a Russian work that the convergent upper air flow indeed dominates in a high pressure area. The figures showing the flow structure in high pressure areas have been reproduced by KÖPPEN²⁹, and one can recognize the complete agreement with our scheme. Two out of the four types represented show a pronounced convergence, whereas the third shows a consistent and strong northerly current, and the fourth does not show any characteristic flow structure. One has to consider that the diagrams are meant to depict the mean air movement in the layers between 2 and 6 kilometres, and therefore show the predominance of the convergence. With regard to the decreasing maxima, 3 cases show a pronounced divergence, and the fourth a weak circular air movement. We find this to be a thorough confirmation that dominant divergence gives rise to pressure decrease whereas convergence gives rise to pressure increase.

Weather types. A certain pressure change can take place in two ways. Air pressure can drop because divergence can cause more air to flow out at higher altitudes than to flow in at lower altitudes, but also because more air is flowing out at lower altitudes than there is flowing in at higher altitudes. Thus, a pressure increase can occur with rising or sinking air. For these reasons, the weather can be entirely different with the same barometer tendency. It is easy to determine the conditions for the different weather types.

If the pressure increase results from the fact that there is more air flowing into the lower layers than there is flowing out of the higher layers, then pressure

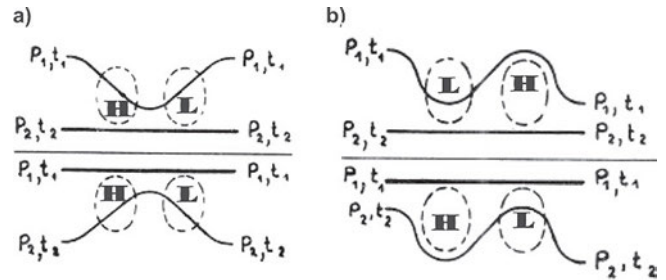


Figure 7: [Stationary and moving pressure areas. Letters p and t denote isobars and isotherms, respectively]^{E7} a) The two forms of stationary pressure areas. b) The two forms of quickly moving pressure areas.

increase is accompanied by rising air masses and the weather must be bad with a rising barometer. However, on the backside of depressions, this weather type is only possible if the depressions move slowly. In the case of great velocity, the air flow on the backside of a low pressure area is divergent because the air moves more quickly than the air flows into the area in the lower layers.³⁰ In these cases, a pressure increase can result only from air flowing in at higher altitudes, which hinders the formation of precipitation. If low pressure areas move slowly, rising air masses are dominant and trigger rainfall activities.

Accordingly, the weather character can be very different in the case of dropping air pressure. A falling barometer due to divergence at higher altitudes is accompanied by rising air masses and has to go along with any quickly moving storm track. If, on the other hand, the barometer falls because there is more air flowing out of the lower layers than there is flowing in at higher altitudes in a high pressure area, then the weather remains fine. MÜGGE³¹ called the two different weather types “polar” and “subtropical,” respectively. Their development depends primarily on the velocity of the cyclones.

Stationary and moving pressure areas. We will consider the differences in pressure and temperature distribution that must exist between stationary and quickly moving pressure areas. The stationary condition can only be maintained if the vertical air mass movement is compensated for. This means, however, that quasi-stationary pressure areas are only possible for the temperature and flow conditions depicted in Fig. 7a. (The solid lines indicate the temperature distribution in the troposphere and therefore also with sufficient approximation the isobaric conditions in the tropopause; the position of the pressure areas on the ground is indicated by dashed circles.) Only if the current at higher altitudes diverges in low pressure areas and converges in high pressure areas, can the air flowing in at lower altitudes be balanced and the required mass inflow above the high

²⁶Cf. HANN-SÜRING, Lehrbuch d. Meteorologie, 4th ed.^{E2}, p. 549, Figures 66 to 69.

²⁷Volume 1933, Issue 12.

²⁸W. MICHEL, Über einige aerosynoptische Merkmale der Änderungen barischer Gebiete. Recueil de Géophysique, Vol. 5, Issue 3, 1932.^{E2}

²⁹W. KÖPPEN, Anzeichen für die Schwächung und Verstärkung der Hochdruckgebiete aus den Pilotaufstiegen. Annalen d. Hydrographie 61, 374, 1933.^{E2}

³⁰Cf., for instance, HANN-SÜRING, Lehrbuch d. Meteorologie, 4th ed.^{E2}, p. 773.

³¹R. MÜGGE, Synoptische Betrachtungen. Meteorol. Zeitschr. 48, 1, 1931.^{E2}

pressure area take place. There is a significant difference between the two types in that the lower pair occurs on the northern side of a warm air advance, whereas the upper pair occurs on the southern boundary line of a cold air advance.

It has already been mentioned that, in the northern hemisphere, the low pressure areas are located in areas of divergent isotherms. If high pressure areas are to be stable, they must be located in zones where the upper air flow quickly grows stronger. KHANEWSKY³² presumes that anticyclones develop due to the banking of cold polar air moving towards lower latitudes. The upper winds represented in the location cited clearly show that the north-easterly current reaching high altitudes on the eastern side of the high pressure area is considerably stronger than the south-westerly wind on the western side, which is in accordance with our scheme. Furthermore, the figures given by RUNGE³³ regarding the pressure distribution of stationary anticyclones at higher altitudes also entirely coincide with the scheme in the upper part of Fig. 7a. RUNGE wants to explain the development of a high pressure area only by the presence of two different air currents, however, one has to consider that the deflecting force cannot readily be presumed to induce a banking.

Fig. 7b shows the two possibilities of pressure and temperature distribution for quickly moving pressure systems. If air movement above a high pressure area is weak, then there is no convergence in the upper layers. Thus, the high pressure area collapses due to the divergence in the lower layers. The collapse will be enhanced if there is divergence at upper layers on the front side of a new low pressure area. This conclusion is an attempt at a theoretical derivation of weather rules based on the working hypothesis just described.

Weather rules based on the divergence of high-altitude winds. The consequent application of the principle of divergence makes it possible to draw a number of conclusions from upper level charts for future weather development.

1. *Divergent high-altitude winds must result in a general pressure drop if they are not compensated for by a strong convergence at lower altitudes.* This rule readily follows from the previous reflections. If there are no measurements of high-altitude winds available, then divergent isotherms can also indicate high-altitude divergence and lead to the rule:
 - a. *If the isotherms show a distinct divergence that is not limited to the ground layers, there will be pressure drop.*

The following rule is in direct relation to rule 1a:

- b. *Cyclogenesis only occurs in the “delta” of frontal zones.*

For convergent areas the corresponding rule is as follows:

2. *Convergent high-altitude winds generally must generate a pressure increase unless they are compensated for by a divergence at lower altitudes.*
 - a. *If the isotherms show a distinct convergence, which is not limited to the ground layers, a pressure increase will result.*
 - b. *There is never cyclogenesis in the “catchment area” of a frontal zone. Despite large temperature contrasts, there is rather a general pressure increase.*

The following conclusions are particularly significant with regard to the weather forecast:

- 3a. *A low pressure area will approach more quickly the faster the square of the velocity in the direction of the wind decreases from the core to the front side.* Since the kinetic energy increases in proportion with the square of the velocity, the change in the squared velocity is always decisive with regard to pressure changes. Thus, a decrease of the wind velocity from 60 to 50 m/sec must result in a tenfold pressure change in comparison to a decrease of the velocity from 10 to 0 m/sec.
- 3b. *In the case of a strong upper air flow on the outer side of a low pressure area, the low pressure area will not approach unless the air movement towards the core area further increases.*

This results in the following conclusion for the development of pressure areas:

- 4a. *A low pressure area with weak high-altitude winds will be filled up, and a high pressure area with weak high-altitude winds will disappear.*
- 4b. *A low pressure area with strong high-altitude winds will remain capable of development, and a high pressure area with strong high-altitude winds will not weaken.*

The position of the divergences is important with regard to pressure areas:

- 5a. *If the upper divergence coincides with the low pressure centre, the low pressure area remains stationary.*
- 5b. *If the upper convergence coincides with the high pressure centre, the high pressure area remains stationary.*

³²W. KHANEWSKY, Zur Frage über die Konstitution und Entstehung hoher Antizyklonen. Meteorol. Zeitschr. 46, 81, 1929.^{E2}

³³H. RUNGE, Entstehung hoher Antizyklonen. Meteorol. Zeitschr. 49, 129, 1932.^{E2}

A number of these rules have already been confirmed by MICHEL's results, others formed the starting point for this study, and the conclusions have, to a large degree, been correct. The proof shall soon be provided by the discussion of specific examples.

The further development of synoptic aerology is a precondition for critically examining the validity of the views outlined here for every single case.

Endnotes

E1 ERIK HERBERT PALMÉN (1898–1985) was a Finnish meteorologist. He is known for his work on cyclones and jet streams. Inspired by TOR BERGERON^{E8}, PALMÉN began working on cyclones in the 1920s in collaboration with JACOB BJERKNES. After the Second World War, PALMÉN moved to the University of Chicago to join CARL-GUSTAF ROSSBY. He made important contributions to the “Chicago School.”

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- E3 WILLIAM HENRY DINES (1855–1927) was a British meteorologist. DINES is known for his work on upper air observations and instrumental design for kite and later balloon observations. The two papers cited here are part of a series of articles, some of which are better accessible:
- DINES, W.H., 1912: The free atmosphere in the region of the British Isles. Third Report. The calibration of the balloon meteorograph and the reading of the traces. – *Met. Office Geophys. Memoirs* **1**, 145–152.
- DINES, W.H., 1912: The Vertical Temperature Distribution in the Atmosphere over England, and Some Remarks on the General and Local Circulation. – *Phil. Trans. Royal Soc. London A* **211**, 253–278.

- E4 FELIX MARIA EXNER (1876–1930) was an Austrian meteorologist who introduced theoretical mechanics into meteorology. He was professor at the University of Innsbruck and director of the Austrian weather service. EXNER also was co-editor of the *Meteorologische Zeitschrift*.
VOLKERT, H., 2007: Exner-Ewarten, Felix Maria von. – In NORIETTA KOERTGE (Ed.), *New Dictionary of Scientific Biography*, Charles Scribner's Sons, ISBN 978-0684313269, 425–427.
- E5 Sir WILLIAM NAPIER SHAW (1854–1945), was an influential British meteorologist. He had various positions at Cambridge University and acted as director of the Meteorological Office.
BURTON, J., 2004: William Napier Shaw – father of modern meteorology. – *Weather* **59**, 307–308.
- E6 SCHERHAG, R., 1934: Die Entstehung des Ostseesturms vom 8. und 9. Juli 1931. – *Ann. Hydrog. Marit. Meteorol.* **62**, 152–162.
- E7 All figures are translated. The original figures (except Fig. 6) have no caption.
- E8 TOR BERGERON (1891–1977) was a Swedish meteorologist of the “Bergen School” of meteorology (see E1). Among numerous other achievements, Bergeron proposed a mechanism for the generation of rain in clouds, further developed and confirmed by WALTER FINDEISEN (Bergeron-Findeisen process, see: FINDEISEN, 1938; STORELVMO and TAN, 2015)
FINDEISEN, W., 1938: Die kolloidmeteorologischen Vorgänge bei der Niederschlagsbildung (Colloidal meteorological processes in the formation of precipitation). – *Meteorol. Z.* **55**, 121–133. (translated and edited by VOLKEN, E., A.M. GIESCHE, S. BRÖNNIMANN. – *Meteorol. Z.* **24** (2015), DOI: [10.1127/metz/2015/0675](https://doi.org/10.1127/metz/2015/0675)).
STORELVMO, T., I. TAN, 2015: The Wegener-Bergeron-Findeisen process – Its discovery and vital importance for weather and climate. – *Meteorol. Z.* **24**, 455–461.
- E9 GERHART SCHINZE (1899–1982), was a German Meteorologist known for his work on air masses.
- E10 In 1909, GABRIEL GUILBERT, a french meteorologist, published a number of empirical rules on weather forecasting, with which he had won the first prize in a forecast competition in Liège, Belgium, in 1905. His rules were based on surface observations. He had a notion of an equilibrium between wind speed and pressure gradient, deviations from which would lead to deepening or filling of cyclones. A second set of rules concerned the divergence of surface winds, which according to him leads to falling surface pressure. GUILBERT's rules were much criticised at that time (REUTER, 1954).
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- E11 SCHERHAG, R., 1933: Die Luftdruck- und Temperaturverteilung in der Höhe bei der Bildung des Ostsee-Orkans vom 8./9. Juli 1931. – *Meteorol. Z.* **50**, 467.
- E12 HANS ERTEL (1904–1971) was a German meteorologist. He is well known for his contributions to theoretical hydrodynamics, including concept of vorticity (known as Ertel's theorem or Ertel's vorticity).
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- E13 ALBERT DEFANT (1884–1974) was an Austrian meteorologist and oceanographer. He worked at the Austrian Weather Service and was professor at the University of Innsbruck before moving to the Friedrich-Wilhelms-Universität in Berlin in 1926. He worked on atmospheric circulation and its variability. In Berlin, DEFANT became a leading figure of German oceanography. After the Second World War DEFANT returned to Innsbruck.
BRÖNNIMANN, S. and F. FREI. 2008: Defant's work on North Atlantic climate variability revisited. *Meteorol. Z.* **17**, 93–102.
- E14 CHARLES ALFRED ANGOT (1848–1924) was a French meteorologist.
- E15 WLADIMIR KÖPPEN, (1846–1940) was a German geographer and climatologist. After positions in St. Petersburg, Russia, KÖPPEN 1875 became head of the new Division of Marine Meteorology at the German naval observatory (Deutsche Seewarte). He was editor of the *Meteorologische Zeitschrift* from 1884 to 1891. KÖPPEN is perhaps best known for his climate classification, variants of which are still in use today.
KÖPPEN, W., 1884: *Die Wärmezonen der Erde, nach der Dauer der heissen, gemässigten und kalten Zeit und nach der Wirkung der Wärme auf die organische Welt betrachtet* (The thermal zones of the earth according to the duration of hot, moderate and cold periods and to the impact of heat on the organic world). – *Meteorol. Z.* **1**, 215–226. (translated and edited by VOLKEN, E. and S. BRÖNNIMANN. – *Meteorol. Z.* **20** (2011), 351–360, DOI: [10.1127/0941-2948/2011/105](https://doi.org/10.1127/0941-2948/2011/105)).
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